This paper was cleared by ASC 00-2307 on 15 November 2000

Reality and Surreality of 3-D Displays: Holodeck and Beyond *

Darrel G. Hopper

Air Force Research Laboratory
Mailing Address: 2255 H Street, Bldg 248 Rm 300, Wright Patterson AFB OH 45433-7022
Telephone: (937) 255-8822, *Fax:* (937) 255-8366, *E-mail:* darrel.hopper@wpafb.af.mil

ABSTRACT

Most 3D displays are really just 3D models projected on 2D devices. Such 2D views sample key features of human vision processing of 3D scenes, via techniques such as converging lines and hidden surfaces, to depict relative depth. Yet, human vision actually processes more information from 3D scenes than can be captured by 2D sensors or presented on 2D displays. Approaches to true 3D and their applications will be reviewed. The Holodeck of science fiction will be examined for ultragrand technical challenges. Beyond the surreal concept of the Holodeck is the reality that significantly better 3D display systems are possible.

Keywords: true 3D displays, multiplexed 2D display (autostereoscopic), volumetric display, e-holography, holodeck, nanoelectronics, avionics, ideal displays

INTRODUCTION

Nature—the Ideal Display. The human visual system (HVS) evolved to view the real world. Nature's performance specification includes 3D. And true 3D, not just 3D models rendered on 2D hardware. Hopper[1a] presented a vision of displays of the future. Hopper[1b] recently assessed the limitations imposed by current displays versus natural imagery. In this paper the 3-D aspects of this deficiency are examined. Opportunities for significant progress are discussed.

Evolution. New technology produces just enough performance—minimal resolution or an aspect of 3D—to be usable and, thus, enable first generation products. Improvements then yield better performance products and expanded applications every few months. During each subsequent technology iteration there is resistance from some in the research community who attempt to 'prove' the next generation of hardware is unnecessary. However, the general population then routinely defies the so-called experts by adopting the improved technology anyway. Television was rejected because it would take homemakers from their chores—TV came anyway. Color was rejected as not being a significant improvement over black & white—color came anyway. Now some say that higher resolution 2D and true 3D are both not necessary—and they are wrong again. Rollout of high-definition television (HDTV) has commenced. Progress on true 3D is being demanded.

Confirmation bias prevails all too often in research. Models are limited, at any particular time, by both available hardware and understanding of human capabilities. People tend to overlook the unfamiliar. The research community should baseline itself on Nature's model—not on the hardware of the day—when declaring what improvements are wanted. Progress is paced by the rate of hardware improvement—but the vision is constant: create a display with all the qualities of Nature's. Nature is 3D.

Limitation. The opposite of the "evolution resistance" community is that wild group that wishes into existence new laws of nature. Holodecks are confined to a room but include solid images with physical presence—but mass is not a feature of the physics of holograms. Holodecks require complex skin-embedded haptic displays or brain-implanted chips—but neural mathematics is mostly not understood. Concepts such as the holodeck and telematter require a physics and mathematics presently unknown—thus, they may require centuries or millennia to be invented.

* Invited Keynote Paper in the ***Electronic Information Display Conference*** of Society for Information Display ('SID@EID'), held at the ExCel Conference and Exhibition Centre, Central London, England UK (Nov 21-23, 2000).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Reality and Surreality of 3-D Displays: Holodeck and Beyond**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Research Laboratory Wright-Patterson AFB, OH 45433**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

3D DISPLAY BEFORE ELECTRONICS

Megasecond Generation for Gigasecond Display. Knowledge of how human 3D vision works originates from art. The creation, or "image generation," of art objects requires hours to years (N x 32 megaseconds), but the corresponding art display time frame is years to millennia (N x 32 gigaseconds). Much of the Natural world scene has been semi-permanently modified by human 3D art.

2D Art. Painters and sketchers struggled for millennia to develop techniques to convey depth perception cues to the human consumers of their 2D art products. Photographers joined this activity in the 1800's. Techniques developed assumed a fixed position and perspective of the viewer relative to the scene depicted, and included:
(a) convergence of lines;
(b) scale of relative sizes;
(c) distance of focus;
(d) coverage or erasure of hidden surfaces or lines; and
(e) effects of light (sources, shadows, shadings, colors, textures, specular and diffuse reflections, et cetera).

3D Art. Human developers and consumers of art wanted more than 2D media could depict. Hence, 3D media were developed. With 3D art the response of viewers to vergence cues was included (differentiation of the slightly different angles of view of the left and right eye). Motion became a feature of many 3D art forms; and haptic displays (mass, touch, and feel) became integral features as well. Also, viewers gained control of their direction and distance from objects—they became free to adopt an infinite number of perpectives by moving either themselves or the object—just as they do with Natural world objects of non-human origin. Examples of 3D art media include clothing, jewelry, diorama, vases, statues, kites, musical instruments, furniture, architecture (buildings, bridges, tunnels), interior decoration, landscaping, agriculture, artificial plant species, domesticated animal breeds, vehicles (carts, carriages, wagons, ships, trains, automobiles, airplanes). The 3D art media also encompass (a) film-based multi-perspective photography (stereoscopic pairs for a single-user; immersive 360° panoramic scenes via tiled 2D for multi-viewers) and (b) film-based holography.

Hologram. A hologram is a two-dimensional intensity pattern, I(x,y), formed by two coherent light beams of the same wavelength. A real hologram is typically formed by (1) splitting a laser beam to create two coherent beams of the same wavelength, (2) directing one, called the reference beam, to fill a specified area on a recording plane, while (3) reflecting the second, called the object beam, off of a real object onto the recording plane. The differences in both amplitude and phase between the reference and object beams are converted to intensity by the response function of the recording material at each point in the recording plane. The hologram appears to the eye to be noise—random spots, blobs, and shapes of light and dark areas. Microscopic examination usually reveals some degree of organization in the form of domains of parallel lines (so-called fringes, or fringe patterns). Illumination of the recorded material ("hologram") with coherent light at a specified wavelength and direction of arrival produces a full parallax virtual image of the original object. The hologram encodes the angle of arrival of beams from the real object and, thus, multiple perspectives (look-around) are available in the play-back image. As the hologram read-out is a diffractive phenomena there is no real image formed except at the eye, just as in natural world imagery—thus, depth can be correctly portrayed without artifacts (such as eye focusing at the position of a screen in a CAVE, rather than the intended position of the image).

Circular Multiplex Hologram. Holograms may be categorized as full parallax (FP) and horizontal-only parallax (HP). An example of the latter is the multiplex hologram, which relies on the fact that humans seem to obtain depth cues from vergence only in a plane that includes both eyes. A circular multiplex hologram is produced as follows:
(1) Standard 35-mm slides are shot at N (dozens to hundreds) of carefully selected increments of angle along an arc (or full circle) all looking inward at a real object or person located at the origin. The size of the increments is made so small that the scene at the origin appears constant at any point within the increment;
(2) Each frame of 35-mm film is illuminated with a laser beam; the resultant modulated 35 x 35 mm beam is compressed horizontally and stretched vertically resulting in a reshaped image of about 1 x 250 mm by use of a special anamorphic lens system;
(3) The reshaped image is now treated as an object image in regular holography and is made to arrive, along with the laser reference beam, at a recording plane to expose a 1 x 250 mm segment;
(4) Film placed at the recording plane captures the N slit holograms at 1-mm increments, and a slit aperture is used to prevent cross-talk during the dozens of sequential exposures. The developed film is curved once into to a predetermined radius and re-played by illumination from inside. Viewers outside of the illuminated film see different perspectives in each eye and these perspectives change as the viewer moves around or as the hologram rotates. A circular multiplex hologram is, essentially, just multiplex photography.

Dynamic Art. Time changed static arts in many ways. During the 19th century moving pictures added time to 2D photography via mechanical projectors, which gave way to electrical motor driven models (electromechanical). During the past two centuries electromechanical instruments in control panels for industrial plants, trains, autos, and airplanes added not only time, but an element of true 3D: the fronts of instruments viewed by operators comprised several dynamic elements (needles, spheres) with real depth.

3-D DISPLAY ENABLED BY ELECTRONICS

Electronic Art. Electronic computers, analog and digital, have dramatically influenced art. Electronics added processing to art beginning in the middle of the 20th century. Both the static and dynamic arts began their electronic makeovers about 1940—just 60 years ago. Analog electronics ruled until about 1980 when it began to give way to digital electronics. Analog television began commercially about 1939 based entirely on real-time image capture, transmission, and display. Digital television began for image capture/generation and transmission in the 1980s and for display, about 1998. In the motion picture arts the electromechanical projectors circa 1900 lasted 100 years and just initiated a transformation to digital electronic projectors circa 2000. Traditional arts (painting, drawing, sculpture, music, design) are adapting electronics as part of expression and creativity at an ever stronger pace.[2] *Regarding 3D, both television and computer image generation enabled rapid shifts in viewpoint and creation of synthetic scenes—techniques unavailable before electronics. Compelling presentation of 3D on 2D devices is based on the perspective provided to the viewer.*

Electronic Displays. There was only one electronic display technology in 1940: cathode ray tube (CRT). Circa 2000 there are two dominant display technologies: CRT and flat panel active matrix liquid crystal displays (AMLCD). Image sampling for CRT screens comprises continuous lines with sample fidelity determined (a) vertically by the number and density of lines and (b) horizontally, within a line, by the density of inorganic phosphor particles embedded in a white binder material and electron beam spread functions. Image sampling for AMLCD screens is in the form of a 2D array of picture elements (pixels). Usable AMLCDs for image presentation appeared ~1988 when pixel size decreased below 325 µm with screen size about 3 in. diagonal (resolution 30 kilopixels); as of 2000, direct-view pixel size is down to 120 µm with screen size up to 42 in. (resolution up 300X to over 9 megapixels).

Electronic 3D Schema. Electronic 3D display is extremely immature due limitations in both hardware device technology and humanware understanding of eye-brain scene processing for depth cues. The status of electronic 3D is turmoil. Iterative efforts over the past 30 years or so may be described as comprising a process of "try and fail, try and learn, try and succeed, but just a little." Various attempts provide an insight here and there. Gradually, some useful true 3D devices and display systems will evolve (see next section). The technology challenges are multidisciplinary and require simultaneous consideration of evolving status of knowledge of hardware, software, and humanware.

Compelling 3D via Standard 2D Electronic Display. Standard electronic displays present a single 2D image, or perspective, to the viewer at a "flickerless" frame rate of 60 Hz (16.7 ms samples). Electronic 2D displays typically take advantage of all of the 2D art tricks and techniques (see above) to convey many compelling features of 3D scenes on 2D electronic display devices. The human vision system perception of such displays as containing depth cues is a natural consequence of perspective ("eye position"): (a) camera angle and location relative to a real world scene or (b) computer image generator reference point and and rendering algorithms by which a 3D model is transformed into a 2D view of a virtual world scene. *Rendering algorithms that covey 3D depth cues on 2D perspective views include hidden line removal, shading, texturing, scale, transparency, translucency, reflectivity, motion, and relative motion.* Fidelity (believability) of dynamic perspective image generation is limited by sensor resolution or computer power, transmission bandwidth, and display resolution.

Stereoscopic Electronic Display. The 19th century photographic stereo pair became electronic in the 20th. The aforegoing electronic display discussion assumes one view (same perspective) presented to both eyes. In Nature each eye has a slightly different perspective. One can invoke this feature of the 3D vision system with two cameras (imaging sensors) separated by the inter-pupil distance (about 63 mm), both aimed at same point and focused at the same depth). Similarly, computer generation can be accomplished for two "pupil" position viewpoints. Non-human scale scenes (subatomic to intergalactic) can be modeled for view. One may then use standard 2D devices at 120 Hz to present interleaved left/right-eye views via filters:
(a) red/blue color; (b) left/right circular polarization; or (c) on/off temporal shutters. Complications include loss of resolution, restrictions on head motion, and head mounted equipment (glasses, head/eye trackers).

Microsteropsis. Siegel[3] of Carnegie Mellon University demonstrated that a binocular perspective disparity that is just a few percent of the nominal 65 mm human interocular separation is enough to stimulate depth perception. This perception, or microsteropsis, purportedly is easier to look at than the stark, stressful stimulus presented by geometrically correct virtual reality displays.

Computed Hologram. Mathematical definitions of holograms exist and enable their computation for any 3-D spatial model of an object or collection of objects. A hologram is a summation of phased arrays, ultracomplex phased arrays, one for each point in the 3-D spatial model. That is, each volume element sample (voxel) of the 3-D spatial model is transformed into a 2-D phased array filling the entire area of the 2D hologram with *fringes whose direction, thickness, and pitch encode the phase, amplitude, and direction of light over a range of angles emanating from the voxel* to the field of view represented by the hologram. Complex scene objects cannot be computed in real time. However, digital holograms computed off-line can be stored, recorded, and played back as if the real scene actually existed. One storage mechanism is, of course, film. Thus, circular multiplex holograms can be computed and recorded on film to increase the range of objects that can be recorded. With far more computational power full multiplex holograms can be produced. The hologram pixel (sample of the 2-D hologram) should be 500 nm in size and 14 bits in grayscale for adequate discrete representation. For digital storage large farms of hard drives are required, even for small area holograms of complex 3-D scene models. For visual display (play-back) only film comes close to satisfying this sampling requirement.

Flat Multiplex Film Hologram via Tiled Computation and Exposure. The most impressive computational holograms to date are the very, very large (1 x 1 m) ultrahigh quality full color holograms for advertising produced beginning in 1999 using holographic photopolymers. Fabrication is an extremely expensive and laborious process comprising (a) approximation of the full hologram as a mathematical sum of some 10^8 small, two-dimensional tiles (about 10 x 10 mm each); (b) computation and storage of the full hologram for just for one tile (about 10 gigabytes); and (c) exposure of the corresponding tile position within a 1 x 1 m photographic negative. A flat, multiplex hologram is full holography except for the tiling error. Parallax exists in both directions and look-around field of view approaches ± 90°. A sampled representation of the finished hologram, I(x,y), would require some 4×10^{18} pixels.

BASIS SETS FOR VOLUMETRIC IMAGES

Voxels. A fundamental basis set for 3D images is to a three-dimensional array of voxels. The voxel is an volume element $v(x,y,z, \Delta x, \Delta y, \Delta z)$ located at a point $p(x,y,z)$ with dimensions Δx, Δy, Δz. Light emanating from a voxel is a function of direction, intensity, and wavelength. Directions comprise all 4π sr from $p(x,y,z)$ and may themselves be sampled as part of the voxel representation. In some cases the intensity might be split into its component amplitude and phase functions, which may each also be discretized (sampled). Wavelength may also be discretized. The sampled representation may then be digitized.

Fonts. One might use the concept of font to model 3D images just as one does in 2D. Fonts are sets of symbols comprising pre-determined arrangements of pixels or voxels. Digital bit maps for characters comprising 3D symbols can be precomputed, stored, and accessed when needed via look-up tables just as one does now for 2D sets. Font complexity ranges from 3D lines to megapyramid volumetric images.

MARKET CONSIDERATIONS

Applications of 3D. Wants exceed the possible in all categories of displays—especially 3D.[1] However, if requirements are written based on current device reality, then some significant needs can be met. Examples include sparse symbol set problems such as situational awareness (SA) for air traffic control (ATC) or radar warning receivers (RWR). Human factors part-task combat pilot and air traffic controller studies exist showing specific situations in which true 3D display of dynamic information (e.g. threat warning effectiveness, relative motion of 3D object set in ATC simulation) significantly improves performance over 2D.[4a, 4b] Not all requirements are based on current device reality and require high risk research. Examples include 3D television with high fidelity volumetric images of persons right down to their eyes for teleconferencing by dispersed command and control team members.

Commercial Value. The value-added engineer (VAE) for consumer products removes features not needed for, or capable of enabling, market success. So far, 3D has appeared in many modes in exhibitions, but has not achieved wide market acceptance anywhere. Economically viable applications are restricted to niche markets—researcher scientists and design engineers. The value added by circa 2000 3D hardware over 2D display of 3D scenes and models is not compelling to most people for most applications. Mass market success will require significantly better 3D hardware.

Translucency versus Opacity. Hidden line removal (opacity) is a key feature and visual advantage, but computational albatross, for the presentation of (a) 3D models displayed on single 2D devices, (b) 3D models displayed on laterally multiplexed images from 2D devices (lateral multiperspective 2D), and (c) full computational electronic holography presented on currently non-existent devices. See-through (translucency to transparency) is a key feature and visual disadvantage of (a) 3D models displayed on depth-multiplexed images from 2D devices, (b) volumetric direct-write devices, and (c) approximated computational hologram limited to the fidelity the available SLM devices can display.

DEVICES FOR ELECTRONIC 3D

Electronic holography. Holograms are 2-D interference patterns and may, in principal, be written on a 2-D recording medium whose response is a function of intensity (e.g. photographic film, charge pattern in a photorefractive medium) or of phase (liquid crystal medium).

Spatial Light Modulators. Electronic devices that modulate light are called spatial light modulators (SLM). Intensity, phase, and amplitude can be modulated. Devices are based on light valves, photorefractive crystals, and acousto-optic cells. Light valves can be 2-D or 1-D devices based on transmissive or reflective liquid crystal dispays, 2-D or 1-D devices based on reflective digital micromirror devices (DMD), or 1-D grading light valves. Photorefractive crystals include tantalum dioxide, lithium niobate, and bismuth silicon oxide, and can be used to fabricate devices that modulate phase (or amplitude if combined with polarizers). The acousto-optic modulator (AOM) cells are used to modulate or deflect a beam. Most SLM devices can be fabricated in a variety of ways for a range of applications. For example, LCDs are ideal for phase modulation of plane polarized laser beam expanded to fill the device aperture. However, LCDs can also be used to direct a series of 2D images to segments of a horizontally divided headbox. A reflective, oscillating circular membrane “drum head” synchronized with a high speed (>180 Hz) 2D display acts as an SLM when used to create a translucent volumetric display.

Visceral Aversion to Head-Mounted Equipment. Users tend to exhibit a visceral aversion to head-mounted equipment. Companies that are designing, manufacturing, and marketing head mounted displays still do not use them in their own offices. Thus, 3D approaches that are autostereoscopic (that is, no-head gear is required) are preferred.

APPROACHES TO TRUE 3D

True 3D Electronic Display. True 3D means that multiple perspectives, usually more than two, are simultaneously presented to the human vision system from the electronic display system. Approaches to true 3D are multiplexed 2D, volumetric, and holographic.

Pre-Recorded vs. Real-Time. The multiplexed 2D and volumetric approaches can support pre-recorded or real-time implementation, more or less, with circa 2000 technology. The holographic approach can only support pre-recorded implementation due to limitations in computing power and device capability.

3D via Multiplexed 2D—Lateral Scene Sampling. Multiplexed 2D has two general forms depending on how the 3D scene is sampled: lateral or depth sampling. In lateral segmentation, the field of view is sampled along the interpupilary axis—usually horizontal 20° bins—and a 2D perspective appropriate for each segment is generated from a 2D sensor, or 2D image generator. Each generated perspective drives a 2D display device whose image is optically projected into the correct lateral position. Each pupil intercepts a different perspective view. Left/right head motion causes each eye to intercept different views. Hence, depth cues derive from eye-brain processing of each instantaneous stereo pair. Horizontal parallax (“look-around”) is presented but vertical parallax is ignored.

3D via Multiplexed 2D—Depth Scene Sampling. In depth segmentation, 2D image slices at each sample depth plane are generated on a 2D display device and reflected from an oscillating mirrored membrane whose motion is synchronized with the 2D display. Sparse, see-through scenes and symbol sets can be presented. Transparency limits applications. Images are flat and the number of image planes/scene complexity is severely limited. Jitter is a problem as the synchronization of the video image generation must be matched to the motion of the oscillating screen.

Volumetric. Volumetric displays generate points or continuous lines via direct-writing. The points or lines act as light sources. One version involves a rotating reflective/diffusive helical screen synchronized with a visible laser beam; the laser beam is modulated and scanned within AOM’s; jitter is a problem. Another version involves rotating concentric circles of light emitting diodes (LED). Two others use infrared lasers: one scans an array of optical fibers terminating in a voxel with upconversion phosphor, and another has two co-scanned beams drawing lines in a solid matrix block doped with two photon absorption species,

$$\lambda_{1\text{-IR}} + \lambda_{2\text{-IR}} \rightarrow \lambda_{3\text{-VIS}} + \text{ phonon .}$$

Holographic. Electronic holography with precomputed holograms played back as film strips is possible provided the scenes are very simple (stick drawings) to accommodate limitations of circa 2000 devices (AOMs), computers, and communications. Nanoelectronics fabrication techiques now being matured by the integrated circuit industry might one day enable fabrication of 25 nm hologram pixels (hpixel) across 100 sq. in. of a 16 in. wafer. The resulting sampled hologram (10^{14} hpixels) might correspond to a true 3-D resolution of 1.5 gigavoxel in a 30^0 FOV by 2100.

ELECTRONIC HOLOGRAPHIC DISPLAY DEVICE CHARACTERISTICS

Hologram Pixel Size. The capability of a holographic display device to generate a realistic image is defined by its pixel size, modulation, and grayscale. The information content of a good quality horizontal-parallax-only computer generated hologram (CGH) is about 10^3 times greater than for a 2D image.[5] A full-parallax (vertical as well as horizontal) CGH would encode 100 times more information, or 10^5 times that of a 2D image. Current 2-D direct view flat panel display pixels range from 120-296 μm (41-100 arcseconds @ 0.61 m); miniature displays (projection image source devices) are now 12-24 μm.[1b] Thus, holographic device pixels would need to be about 200-nm. Separately, one would expect the pixel size to be comparable to the wavelength of light, or about 500 ± 150 nm for visible. Hologram readout is a diffractive interference phenomenon, which becomes significant when electromagnetic radiation encounters structures (e.g. pixels of LCD or GLV devices) whose feature sizes are near that of the wavelength.

Holographic Tolerance to Defective Pixels. Lithography now permits the fabrication with 150 nm design rules. Nanoelectronics has enabled fabrication of realistic SLMs for electronic holography, even if defect rates are high. A hologram, unlike the other 3D techniques, is not a positive image, but a spatially modulated image encoding direction as well as intensity, color, and grayscale information. The modulation/demodulation carrier is a coherent, singular wavelength light beam (i.e. laser). Each hologram pixel contains information about the entire encoded image. Defective pixels add noise but do not destroy the viewability of the image playback.

Phase and Amplitude Modulation. Hologram intensity may be broken into two parts: (a) amplitude and (b) phase. Two separate devices may be designed for these two parts, which would be combined optically. Lucente[14] has modeled this approach.

Holodeck. Full true 3D display technology is represented conceptually by the Holodeck of science fiction and is a millennial challenge to be met by the dawn of the 31st century: over 22 teravoxels are needed. The holy grail of 3D display, the Holodeck with ultra-high resolution room-filing imagery with hidden lines removed plus haptic, may be not be possible prior to the year 3000, if ever.

IMPLEMENTATION and APPLICATION

Attempts to implement the three approaches to true 3D are reviewed and analyzed below. Commercialization successes are noted.

MULTIPLEXED 2D

Two Views With Head-Slaved Cameras. A pair of cameras slaved to head motion and driving a pair of head-mounted displays can provide depth perception with acceptable human factors. One may think of this approach as “electronic binoculars” or synthetic vision. Civilian applications are limited due to the severely restricted 40-100° field of view. Military applications take advantage of the opportunity to shift infrared imagery into the visual, turning the night into day.

Two Views With Computer Generated Images—Head-Mounted. True 3D with complex images via computation is precluded by circa 2000 processing power and communication bandwidth. Dynamic stereo pairs of computer generated images can be presented via a head-mounted or desk-mounted display. The former suffers from unacceptable computer image latency compared to natural head movement unless content is limited to very simple graphics; also, an accurate head tracker remains a technical challenge.

Two Views With Computer Generated Images—Direct-View Monitor. A monitor version autostereoscopic display with dynamic variation of the two views presented was invented by Eichenlaub et al.[6] at Dimension Technology Inc. in Rochester NY and requires just a coarse head tracker. The DTI approach uses an AMLCD with a special drive scheme (alternate columns comprise left/right eye views) synchronized (1) to two interleaved arrays of vertical backlight tubes and (2) to an LCD shutter with alternating on/off columns. The arrangement is such that the left/right eye view is directed to the appropriate eye for a usable range of head motion. Advantages include the use of many available AMLCDs and the lack of head mounted displays. Drawbacks include the loss of half the horizontal resolution. The DTI autosteroscopic monitor has been commercialized for the product design and data visualization communities.

Eight Views With Precomputed Images. Martin et al.[7] at Litton Guidance and Control Systems in Northridge CA have created a novel multiperspective version of an autostereoscopic system similar in some regards to the DTI system. The Litton system is based on fast CRTs and fast electronic shutters (ferroelectric liquid crystals). In the new Litton system, images for several perspectives (8-20) are projected (sequentially within about 30 ms) from the CRT via a cylindrical lens through synchronously open vertical shutter segments to form a time sequence of 20 mm wide images along the interpupilary axis of the viewer. Each such 20 mm presents a perspective view rendered (computer-generated real-time or, usually, before hand and stored in memory as a "film strip") from a mathematical model of a 3-D graphical world. Each eye sees a different perspective and horizontal head motion enables one's eye to intercept different perspectives to "look around" objects rendered in the foreground to see those placed behind. Litton produced two prototypes, one 25 in. proof of concept and one 50 in demonstrator for a two-person, two-head box display system for a video arcade game. Litton now wishes to explore military applications and has developed a 3-D graphical symbol set for helicopter flight operations (pathway in the sky, landing, vertical and horizontal speed). Litton might produce a 25 inch prototype suitable for installation and use in a research cockpit or research crewstation. Commercialization is underway—Litton is implementing its multperspective display as a two-person console (sit-down, standing) for arcade game (e.g. auto racing).

Twenty Views—Electronic Multiplex Holography. Little et al.[8] at the University of Dayton Research Institute designed a 20-perspective system with 20 displays of corresponding perspective views projected onto a pupil-forming screen (a Fresnel lens and a pair of crossed lenticular lens arrays). The displays were to be small AMLCDs or DMDs. This system was not built. Aye et al.[9] recently suggested a similar multiplexed holographic projection screen.

VOLUMETRIC

Depth Image Slices. The use of a vibrating, reflective membrane synchronized with an overhead CRT was explored about 1990. Difficulties included comprehension of data on transparent image planes (foreground images interfered with background planes), image distortion and jitter (different expansion and speed at center versus edges), and limited frame rate (CRTs and associated drive electronics). Aye et al.[10] proposed an electronic version to address the latter two difficulties: the CRT and membrane are replaced by a ferroelectric LC-SLM and LC switchable diffuser.

Direct-Write Laser on a Rotating Helical Surface. Soltan et al.[11] developed a volumetric 3D display system by utilizing a screen in the form of a helical surface rotating at 600 revolutions per minute. A 36-in. reflective double helix display was fabricated that enabled 20 Hz refresh. Resolution was claimed to be 800,000 voxels per second per color. A portable 12-in. diameter, translucent helix system was also designed. Problems include jitter—sources included the need for 60 Hz not 20 Hz refresh/update; helix wobble, and slight mis-synchronization of helix rotation with voxel addressing. Also, the image is dim due the need to refresh rapidly—the image is formed by integration in the retina of the viewer's eye. Resolution was severely limited by available AOMs used for laser deflection (addressing) and modulation. Far faster SLMs are needed. Scene-filling, high resolution 3D with hidden line removal, as claimed by the Soltan team in its presentations, would require 22 teravoxels per second, or over 30 million times the resolution actually achieved. Also, hidden line removal is impossible with a volumetric approach. Work on this volumetric approach has stopped.

Direct-Write Laser in a Two-Photon Upconversion Cube. E. Downing of 3D Technology Laboratories (3DTL) fabricated a 1-in cube of material doped with two-photon up-conversion sites. Two infrared lasers are intersected in the cube and scanned to create continuous, visible 3D lines. A 6-in. cube is being built for a DoD demonstration program. Strong advantages of this volumetric approach are that it provides (1) lines of light and (2) real images without jitter on which the eye can properly focus. Limitations include lineal writing speed (mm/s at which lines can be drawn) and low up-conversion efficiency (the display is extremely dim even in a darkened room). Also, the image is formed by integration in the retina of the viewer's eye and must be refreshed rapidly. The DARPA Electro-Active Polymer (EAP) program is funding 3DTL to develop more efficient materials for two-photon infrared laser upconversion tailored to desired visible wavelengths by using EAP materials to modify the electromagnetic field near inorganic atoms so as to increase transition probabilities. The new 3DTL materials may enable the creation of a usable true 3D display—one that provides correct vergence and focus cues to the viewer.

Direct-Write Laser into Light Guide Array. Takeuchi et al.[12] of Photera together with Higley of Specialty Devices Inc. in Planar, Texas developed 3D display in which a laser scans the base of a 2D array of light waveguides of varying length (voxel positions). SDI fabricated a 76,800 voxel monitor in 1999.

ELECTRONIC HOLOGRAPHY

Pre-computed Holograms Projected via SLMs
Hopper[13a] reviewed concepts for real-time holographic displays available in the literature before 1990.

Origin of Electronic Holography. Benton et al.[14] introduced the term "electronic holography" with their work published beginning in 1990 and continuing through the present on the display of computed holograms via AOMs. Mathematical approximations were necessary to accommodate limitations in digital computing power (the MIT Connection Machine), communications bandwidth (computer room to laser optics laboratory), and line rendering rate (usable aperture length of AOM cell). The hologram was approximated as a set of lines and each line was segmented into lengths that fit in the aperture of the AOM cell. Hologram complexity was limited to a line outline drawing of objects such as the Starship Enterprise of the science fiction television show StarTrek. The image is formed via integration in the human eye. Excellent images were formed and projected. Improved computers and SLMs are enabling real-time generation of simple line figures. Recent work reported transition from 1-D AOMs to 2D DMDs to enable playback of more complex figures.

Software. Sholler, Meyer, Lucente, and Hopper[13b] considered software for computer generated holograms. The approximations are made as to create the best resolution that the output device (SLM) is capable of producing without violating the Nyquist sampling limit; hologram sample size is typically 500 nm. The resulting CGH eliminates processing and storage of resolution which cannot be displayed on current day SLM devices.

Algorithms. Sheerin et al.[15] have studied the relationship of computer generated holograms and the algorithms used to design them and maintain that only the CGH approach holds the promise of producing synthetic images having the full range of depth cues. It is important to realize that holograms produce synthetic renditions of Natural world images and that computational approximations presently make them less useful than other means of presenting 3D information—better computers and display devices are needed for holograms to live up to their promise.

Threat Warning Display. Thayne, Ghrayeb, and Hopper[13c] demonstrated how the electronic holography technology demonstrated by Benton et al[14] could be developed to realize the true 3D threat warning globe of Reising and Mazur[4] with flyable hardware.

Holographic Voxel Projector. Kelley and Robinson[16] analyzed a holographic voxel projection concept. A multiplex hologram was designed such a 2D pixel image pattern would be transformed into a 3D voxel image pattern by the hologram. Ideally, the concept was to fabricate the hologram and then use it to make any 2D display into a 3D voxel projection display. Unfortunately, the effort failed as no more than 2-3 holograms could be written into a film hologram.

Holographc Television. Burney et al.[17] of Chronomotion Imaging Applications, Inc. claim to have a patent on holographic television, as illustrated in Figure 1. The patent covers the entire process of image capture, storage and display of holograms. A 20 second animated holography cartoon was demonstrated in 1998. Better display devices are needed (see above section on electronic holographic display device characteristics).

CAPTURE → COMPUTER → DISPLAY

CAPTURE	COMPUTER	DISPLAY
CCD Camera or other Means	Storage	Liquid Crystal or other Means

Figure 1. Burney scheme for animated holographic TV.

HUMAN VISUAL SYSTEM—3D

The capacity of the human visual system is estimated in Table I on the basis of the number or resolvable voxels needed in the surface of a sphere surrounding a design eye point given 10 to 10,000 depth layers. One might imagine a person suspended in space but able to look at will in any direction. Full motion video (>60Hz with no computer latency) and full grayscale are assumed in the present discussion--just as in nature.[1]
.

Table I. Number of resolvable voxels in 4π sr.

Depth Layers	2D Acuity	Voxels (billions)
10	50 arc seconds	2
100	50 arc seconds	21
1000	50 arc seconds	214
	20 arc seconds	1,337
	5 arc seconds	21,386
	2 arc seconds	133,660
10,000	2 arc seconds	1,336,600

* Holodeck of Starship Enterprise > 22 teravoxels.

SUMMARY

Three-dimensional displays with true depth and look-around will develop slowly. The fact is that 2D rendering of 3D models provides compelling depth cue information in electronics displays. Pre-electronics art provided many highly effective techniques for conveying to a human vision system, in a convincing manner, 3D information from flat 2D renderings. And 2D display devices are rapidly increasing in capability (resolution, grayshades, pixel density, frame rates).

Nonetheless true 3D (multiperspective depth perception with look-around) will continue to advance along three general approaches:

(1) multiplexed 2D;

(2) direct write volumetric, and

(3) electronic holographic.

Materials and device fabrication challenges noted throughout the aforegoing sections of this paper will be steadily overcome. True 3D, autostereoscopic (no head gear) monitors with usable resolutions (2-20 gigavoxel) should be commercially viable by 2020. A key advance here will be nanoelectronic wafers for displaying pre-computed, high fidelity holograms.

Simple stick diagram (sparse symbol set) holograms are available now and should be commercially viable by 2010 for pre-computed 3D fonts, and by 2020 for real-time computation of holograms of arbitrary 3D symbols. There are important civilian (ATC, art) and military (radar warning receiver, hologram avatar) which can be better addressed with sparse symbol set true 3D displays than by 3D models rendered in 2D.

Multiplexed 2D is on the verge of becoming commercially viable for the arcade gaming industry. Training and education (civil and military) may follow.

Opportunity for progress often appears at the intersections of traditional disciplines, such as electronics, information, biology, human factors, user synergetics. This situation *clearly* obtains for the ultragrand technology challenge of the "holodeck," which requires over 22 teravoxels. This ultragrand challenge is a convolution of many other barriers—including discovering how the human brain works (by 2020) so we can design chips to interface with it from our computers (which will be as capable as our brain by 2030). Haptic displays are in their infancy but are necessary to holodecks; several decades are needed for the creation of truly useful and ubiquitous haptics.

The surreality of the holodeck translates to 100-1000 years of work before we may expect it to move from science fiction to science fact.

The reality of usable true 3D displays will have to overcome several barriers in addition to those of display device fabrication. One barrier is the hype over 3D that has become so commonplace—people want it yet engineers cannot build it. The entertainment industry and imagination fill the gap in the media of science fiction, users see the movies, and want it yesterday. User expectation management is a must.

Another barrier is image generation. Faster computers designed specifically for image rendering are needed. Work is underway at several universities to produce such "warp engines" for rendering images of pixellated 2D displays at 100 megapixels per second; similar work is needed to renter holograms for voxellated 3D.

True 3D presents multifaceted challenges in device creation and system design. Useful products have begun to appear in niche markets that are economically viable and slowly growing. However, true 3D hardware that is affordable yet more compelling than 3D models rendered on 2D hardware will not likely create mass markets until after 2010.

REFERENCES

1. (a) Darrel G. Hopper, "*Keynote Invited Paper* 'A Vision of Displays of the Future," published in *Digest of Society for Information Display (SID) Electronic Information Displays (EID'99) Conference* (Nov. 1999);
(b) Darrel G. Hopper, "1000 X difference between current displays and capability of human visual system: payoff potential for affordable defense systems," in ***Cockpit Displays VII: Displays for Defense Applications,*** Darrel G. Hopper, Editor, Proc. SPIE 4022, 378-389 (2000).

2. Proceedings of the 10th International Conference on Artificial Reality and Tele-existence," National Taiwan University, Taipei, October 25-27 (2000).

3. Mel Siegel, "Just enough reality: a kinder gentler approach to stereo," in *Cockpit Displays VI: Displays for Defense Applications,* Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3690, pp. 173-179 (1999).

4. (a) John M. Reising and K. M. Mazur, "3-D displays for cockpits: where they payoff," in *Stereoscopic Displays and Applications*, Proceedings of SPIE Vol. 1256, pp. 35-43 (1990);
(b) K. F. Van Orden and J. W. Broyles, "Visuospatial task performance as a function of two- and three-dimensional display presentation techniques," *Displays* Vol. 12, pp. 17-24 (2000). vanorden@spawar.navy.mil

5. P. Hariharan, *Optical Holography*, Cambridge University Press (1984).

6. (a) Jesse B. Eichenlaub and Todd Touris, "An in cockpit 'situation awareness' autostereoscopic avionics display," in *Cockpit Displays*, Proceedings of SPIE Vol. 2219, 395-406 (1994);
(b) Jesse B. Eichenlaub, Jamie M. Hutchins, and Todd C. Touris, "Color Flat Panel Displays: 3D Autostereoscopic Brassboard and Field Sequential Illumination Technology, " Air Force Technical Report WR-TR-95-1113 (June 1997), available from AFRL/HECV, WPAFB OH 45433.

7. Graham J. Martin, Alan L. Smeyne, John R. Moore, Stewart R. Lang, Neil A. Dodgson, "Three-dimensional visualization without glasses: a large-screen autostereoscopic display," in *Cockpit Displays VII: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 4022, 203-213 (2000). marting@littongcs.com

8. Gordon R. Little, Steve C. Gustafson, Victor E. Nikolaou, "Multiperspective autostereoscopic display," in *Cockpit Displays*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 2219, 388-394 (1994).

9. Tin M. Aye, Andrew Kostrzewski, Kevin Yu, Nobert Fruehauf, Gajendra Savant, Joanna Jannson, "Multiperspective holographic autostero 3-D display, in *Cockpit Displays VII: Displays for Defense Applications*, Darrel G. Hopper, Editor, 189-195 (2000).

10. Tin M. Aye, Nobert Fruehauf , Mingjun Zhao, Kevin Yu, Yunlu Zou, and Gajendra Savant, "Multiplanar liquid crystal volumetric 3-D displays," *ibid*, 196-202 (2000).

11. Parviz Soltan, Mark Lasher, Weldon Dahlke, Neil Acantilado, and Mal McDonald, "Laser pojected 3-D volumetric displays," in *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3057, 496-506 (1997).

12. Microlaser-Based Three Dimensional Display. Eric B. Takeuchi, Robert A. Bergstedt, David E. Hargis, and Paul D. Higley, "Microlaser-based three dimensional display," in *Cockpit Displays VI: Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3690, 166-172 (1999).

13. (a) Darrel G. Hopper, "Real Time Holographic Displays," Invited Paper in *the Cockpit of the 21st Century—Wlll High Tech Pay Off?*, Proc. 11th IEEE/AESS Dayton Chapter Symposium, pp. 40-49 (28 November 1990); (b) Elizabeth A. Sholler, Frederick M. Meyer, Mark Lucente, and Darrel G. Hopper, "True-3D displays for avionics cockpit and mission crewstations," in *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3057, 478-489 (1997); (c) Jarin R. Thayn, Joseph Ghrayeb, and Darrel G. Hopper, "3-D display design concept for cockpit and mission crewstations," in *Cockpit Displays VI: Displays for Defense Applications,* Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3690, pp. 180-185 (1999).

14. (a) Mark Lucente, Pierre St. Hilaire, Steven A. Benton, D. L. Arias, and J. A. Watlinton, "New approaches to holographic video," *Holographics International'92*, Proc. SPIE 1732, paper 48 (1992);
(b) Ryder Nesbitt, Steve Smith, Raymond Molnar, and Steven Benton, "Holographic recording using a digital micromirror device," in *Practical Holography XIII*, Proc. SPIE (January 1999).

15. David T. Sheerin, Ian R. Mason, Colin D. Cameron, Douglas A. Pain, and Chris W. Slinger, "Quantitative evaluation of 3D images produced from computer generated holograms," ," in *Cockpit Displays VI: Displays for Defense Applications,* Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3690, pp. 186-193 (1999).

16. Shawn Kelley and Charles Robinson, Holographic Voxel Projector, Technical Report WR-TR-93-1059.

17. (a) Michael Burney, Lawrence Dickson, and Bernard Freund, "An all electronic system for the capture, storage and display of volumetric images utilizing holography," in *Cockpit Displays III*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 2734, 227-234 (1996); CIAI and SuperComputing Surfaces, Inc. in Santee CA
(b) Michael Burney, "Converting 3D into volumetric images," in *Cockpit Displays IV: Flat Panel Displays for Defense Applications*, Darrel G. Hopper, Editor, Proceedings of SPIE Vol. 3057, 490-495 (1997);
(c) Michael Burney , "Animated holography," in *Cockpit Displays V: Displays for Defense Applications,* Darrel G. Hopper, Editor, Proc. SPIE Vol. 3363, 416-422 (1998). mburney@ix.netcom.com